

Scaling Laws for the Aeroacoustics of High Speed Trains

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I. Summary

The present study focuses on the scaling of the main aeroacoustic sound sources of a high speed train. The investigations are carried out by measuring in a wind tunnel by means of microphone array technique. The experiments using a 1:25 Inter City Express 3 model were conducted in two different wind tunnels: The Aeroacoustic Wind tunnel (AWB) of the German Aerospace Center (DLR) in Brunswick, which provides nearly perfect acoustically conditions, and in the Cryogenic wind tunnel (DNW-KKK) of the DNW (German - Dutch wind tunnels) in Cologne, which allows measurements at higher Reynolds numbers.

Two different sources of sound with different characteristics are identified from the measurements in the AWB at Reynolds numbers up to $Re = 0.46$ mio: The aeroacoustic noise from the bogie section is dominant for frequencies $f < 6$ kHz and can be characterised by cavity mode excitation. The shape of the spectrum is not velocity dependent within the investigated velocity range. The pantograph is the dominant source of sound above $f = 6$ kHz. It is more tonal noise and the frequency peaks show a strong velocity dependence. These two sources of sound demonstrate that it is not possible to formulate one scaling law for all sources of sound of a train. It is essential to treat every single source separately and to take their characteristics into account.

In order to investigate the noise generated at the bogies at higher Reynolds numbers up to 3.70 mio a second measurement campaign has been conducted in the cryogenic wind tunnel. By cooling down from $T = 300$ K to $T = 100$ K one changes the physical properties of the fluid and the Reynolds number increases by a factor of ~ 5 . Besides, this wind tunnel admits to vary the Mach and Reynolds numbers independently. Drawback of this facility is that it is not optimised for aeroacoustic experiments and reflexions as well as the high background noise level can disturb the results.

The Mach number is kept constant and a Reynolds number variation is realised by varying of the temperature. The first bogie shows only a weak Reynolds number dependence. The deviations are within the measurement accuracy. To go more into detail further investigations with an improved setup are planned.

II. Introduction

Modern high speed trains allow operational speeds up to 350 km/h and for this range of velocities aerodynamic noise is dominant and exceeds all other sources of sound like engine / gearbox noise, noise from aggregates like engine cooling, general noise from the bogies and interaction between wheel and rail. For reducing the aerodynamic noise a detailed knowledge of the distribution and the properties of the sound sources is necessary. In the field of acoustics of high-speed trains both, investigations on the full-scale vehicle as well as testings in wind tunnels on models have been done. Full-scale tests have the advantage, that the measurement can be conducted under real

conditions and appropriate Reynolds numbers. The disadvantage is that these testings only can be performed when the train is already in operation. It is not possible to analyse acoustics during the design process. Nevertheless, most of the earlier publications report on full-scale testings and have their focus on the so-called wheel-rail noise (see Barsikow et al.:^{1,2}). This kind of noise is generated by the mechanical interaction between the wheels and the rails. As already mentioned, at higher velocities aerodynamic noise prevails and in the last years aerodynamic noise became more and more focus of interest. At the same time modern microphone array techniques became an effective tool for the localisation of sound sources (see Martens et al.:³).

To predict the aeroacoustic properties during the design process, wind tunnel testings on down-scaled models are fundamental. Yamazaki et al.⁴ used beamforming techniques for the investigation of aerodynamic noise of a simplified train model in the wind tunnel. The scale of their model was 1:8 and a maximum Reynolds number of about 2 mio was achieved. They focused on noise sources generated by the bogie cavities and the gaps between the coaches. Based on this measurements, modifications for noise reduction were applied. Other wind tunnel studies just point out investigations of parts of trains. One of the main topics is the acoustic of the pantograph (see:^{5,6}).

Still an open issue is a quantitative aeroacoustic study of a train in a wind tunnel. Desirable is an identification of all aeroacoustic sources and the validation of the aeroacoustic measurements for comparisons to full-scale testings.

The aim of the paper is to make a first step for the development of aeroacoustic scaling laws.

III. Methods

Aerodynamic scaling

The Reynolds Number is an important non dimensional parameter in the scope of aerodynamic scaling and can be seen as the ratio of inertia forces and viscous forces. This coefficient can describe the state of the flow (e.g. whether it is laminar or turbulent):

$$Re = \frac{U_{\infty} \cdot L \cdot \rho}{\mu}. \quad (1)$$

Ma denotes the Mach number, $\rho(T)$ the density, L a characteristical length and $\mu(T)$ the dynamic viscosity. Independent of the scale of the model, for a constant Reynolds number one can expect the same flow topology as long as the shape of the model is the same. This holds as long as compressibility effects are not relevant and the Mach number is small enough:

$$Ma = \frac{U_{\infty}}{c} < 0.3. \quad (2)$$

The Reynolds number is a temperature dependent coefficient, because speed of sound, density and viscosity are function of temperature:

For ideal gases the speed of sound c can be computed as follows:

$$c(T) = \sqrt{\kappa \cdot R \cdot T} \quad (3)$$

The adiabatic exponent $\kappa = 1.4$ is constant for diatomic gases.

The ideal gas law provides the relation between density, pressure and temperature:

$$\rho(T) = \frac{p}{R \cdot T} \quad (4)$$

Last not least, the dynamic viscosity is also a function of temperature. It can be calculated using Sutherland's formula:

$$\mu(T) = \mu_0 \cdot \frac{T_0 + C}{T + C} \cdot \left(\frac{T}{T_0} \right)^{3/2} \quad (5)$$

C , μ_0 and T_0 are constants and depend on the medium. Tabula 1 provides all constants for nitrogen and air.

By cooling down from room temperature to $T = 100$ K one can increase the Reynolds number by a factor of about 5, at constant Mach number.

Table 1. Constants for Sutherland's formula for air and nitrogen.

Gas	C [K]	T_0 [K]	μ_0 [1×10^{-6} Pa · s]
Air	120	291.15	18.27
Nitrogen	111	300.55	17.81

Aeroacoustic “cryo” - scaling

The variation of the temperature changes the physical properties of the fluid which also affects acoustics. Mainly, acoustics can be influenced in two ways: in amplitude and in observed frequencies. First, some aspects concerning observed frequencies are pointed out.

As demonstrated later, there are aeroacoustic sources where the frequency is not influenced by the flow velocity within the regarded velocity range at a constant temperature. It seems that the wavelength λ is directly connected to a typical length scale or a volume. This behaviour can be described by cavity mode excitation. For such types of sound sources the frequency will be a function of the temperature, because the speed of sound c changes (eq. 3).

$$f = \frac{c(T)}{\lambda}. \quad (6)$$

For the comparison of data acquired at different temperatures this effect must be considered. In this particular case it is reasonable to use a dimensionless frequency which is nondimensionalised by the quotient of the speed of sound and a characteristically length:

$$f_{norm} = \frac{f \cdot L}{c} \quad (7)$$

This formulation is very similar to the well known Strouhal number:

$$Sr = \frac{f \cdot L}{U_\infty} = \frac{f \cdot L}{c \cdot Ma}. \quad (8)$$

The Strouhal number is a common coefficient to describe another type of sound sources which show a linear dependence between frequency and flow velocity. A famous example for this situation is the Kármán's vortex street which forms behind a cylinder in cross flow. The Strouhal number in

the wake only show a weak Reynolds number dependence (see: Fey et al.⁷).

Also the amplitude or source strength can be influenced by the temperature. In⁸ one can find the derivation for the acoustic source power P of monopole and dipole sound sources, based on the acoustic potential theory:

$$\text{Monopole: } P(t) = \frac{\dot{q}^2(t)}{4\pi\rho c} \quad (9)$$

$$\text{Dipole: } P(t) = \frac{\ddot{G}^2(t)}{12\pi\rho c^3} \quad (10)$$

A monopole can be described by a temporal fluctuating source of mass with source strength \dot{q} . For a dipole the source strength \ddot{G} has the physical unit force. In a first attempt the assumption is made that the source mechanisms is not influenced by the temperature and there is no impact on the source strength. Then, a temperature dependency is expected which is plotted in figure 4(a), with $T = 300$ as reference temperature. The influence of the temperature, which means in this case the influence on density ρ and speed of sound c , causes deviations of the sound pressure levels less than ± 0.25 dB. If experiments show higher deviations, then the source strength must be a function of temperature and/or of the Reynolds number.

Beamforming

For the sound localisation and quantification in aeroacoustic experiments the Delay and Sum Beamforming algorithm in the frequency domain is applied which is on the summation of retarded microphone signals. The principles can be find in the textbook from Johnson and Dudgeon.⁹ Various modifications of the algorithm were necessary to adopt it to the conditions of measurements in wind tunnels. For more details see.^{10–15} Besides noise maps, which map the distribution of sound sources, an integration technique described by Brooks et al.¹⁶ is applied which enables the computation of sound pressure level spectra for specified scan areas.

IV. Aeroacoustic measurements

For all experiments described in this paper a 1:25 scaled Inter City Express 3 (ICE3) model is used. It is designed for aerodynamic testings and therefore it has a low level of itemisation, which is common for such models. For aerodynamic testings the shape of the model is more important than every single detail. For aeroacoustics this may differ, and single components like antennas, cooling intakes or equipment on the roof are important sources of sound. Nevertheless, the main important details are reproduced, namely the bogies, the pantograph and the gap between head car and first coach. For all considerations concerning the Reynolds number described later, as characteristical length the width $L = 0.12$ m of the train is chosen.

A. Measurement in the Aeroacoustic Wind tunnel (AWB)

At first the main aeroacoustic sources are identified by measurements carried out in the Aeroacoustic Wind Tunnel facility (AWB) of the German Aerospace Center (DLR) in Brunswick.¹⁷ Figure 1(a) shows the setup in the test section. The train model is installed on a splitter plate, which has

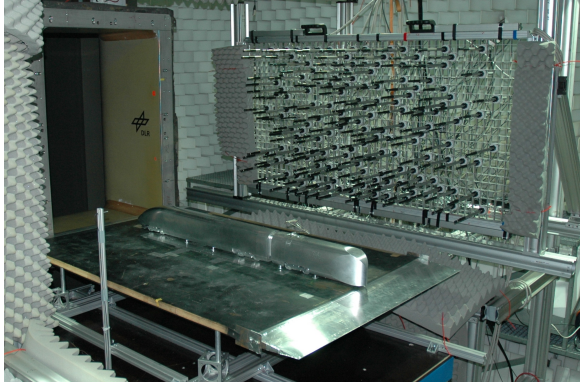
an elliptical leading edge and a sharpened trailing edge. This plate is positioned 10 cm above the lower edge of the nozzle in order to peel off the wind tunnel shear layer. At the leading edge of the splitter plate a new boundary layer is formed which is thinner than the wind tunnel boundary layer. The aim is to keep the thickness of the boundary layer thin in order to ensure a reasonable simulation of the flow underneath the train. In the wind tunnel experiment one expects a Poiseuille flow between splitter plate and train underframe. In the full-scale world the train penetrates the fluid, which is at rest and a turbulent Couette flow will develop. Only a moving belt can provide a better simulation of the full scale world in the wind tunnel, or maybe a mirror model (see Grunwald¹⁸). However, experiences have shown that the setup on the splitter plate is a good compromise which leads to reasonable results, at least for aerodynamic testings.

Figure 2(a) shows source maps for three different third octave bands 2.0, 3.15 and 5 kHz, measured at a flow velocity of $U_\infty = 60$ m/s. The sound pressure level in dB is colour-coded. For the lower frequencies the thirist bogie is the main aeroacoustic source, but for frequencies higher than 5 kHz the pantograph becomes dominant. Also, the gap between head car and first coach and the other bogies are visible in the source maps. Noticeable is that the first bogie is a much stronger source compared with the other bogies. This can be explained by the conditions of the boundary layer: at the head of the train close to the stagnation point the boundary layer is thin which can lead to a strong excitation of the source mechanism. Furthermore, at the front the ICE3 has a spoiler which guides the accelerated flow into the bogie cavity.

A more quantitative representation is given by the focused spectra, depicted in figure 2(b). The three plots show spectra, which belong to the areas of the whole train (blue), the pantograph (green) and the first bogie (red). The spectra show, that for frequencies higher than 5 kHz the pantograph is the main source. Further, the pantograph spectrum has strong tonal components. The spectrum of the first bogie also contains tonal components in the low frequency range < 4 kHz, but its overall shape is smoother and the sound pressure level declines faster for higher frequencies. In order to investigate the characteristics of the sound generation at the first bogie and the pantograph, spectra are presented for different flow velocities between $20 < U_\infty < 60$ m/s, corresponding to Reynolds numbers between $0.153 \times 10^6 < Re < 0.456 \times 10^6$. Figure 3(a) depicts the spectra of the first bogie. The overall shape of the spectra does not change significantly with increasing flow velocity and the two peaks in $f = 2455$ Hz and $f = 3442$ Hz are not flow velocity depended. Obviously, certain cavity modes are amplified and within the considered velocity range no other modes are excited. Measurements at higher Reynolds numbers are essential to find out if higher acoustic modes can be excited, or whether they persist. At this point it is questionable if it is possible to extrapolate these results to a full scale train.

The pantograph noise differs completely from the bogie noise. Here, a strong velocity dependence of the frequencies is observed. The plot over the Strouhal number points out that there must be a nearly linear frequency - velocity dependence. In the spectra one can find several constant Strouhal numbers. For more information see Lauterbach et al.¹⁹

For both, the aerodynamically induced noise from the first bogie and the pantograph a similar power law between overall sound pressure level and flow velocity is obtained. For the first bogie one obtains $L_P \propto U_\infty^{6.22}$ and for the pantograph $L_P \propto U_\infty^{6.12}$.

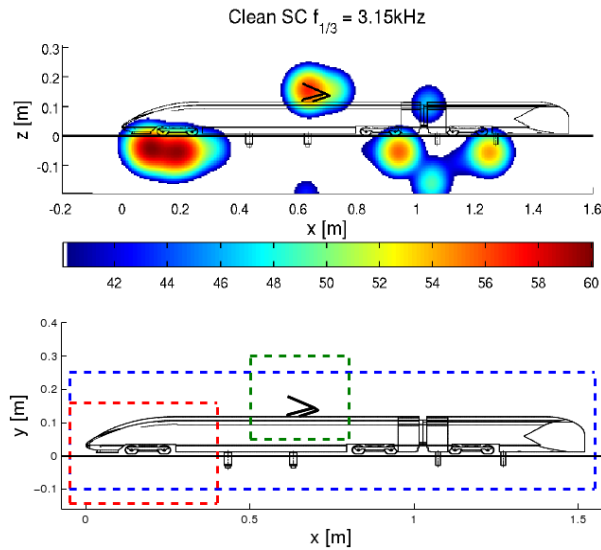


(a) Setup in the AWB: Inside the test section on a splitter plate the model of the ICE3 is installed. In the background outside the flow the microphone array is mounted.

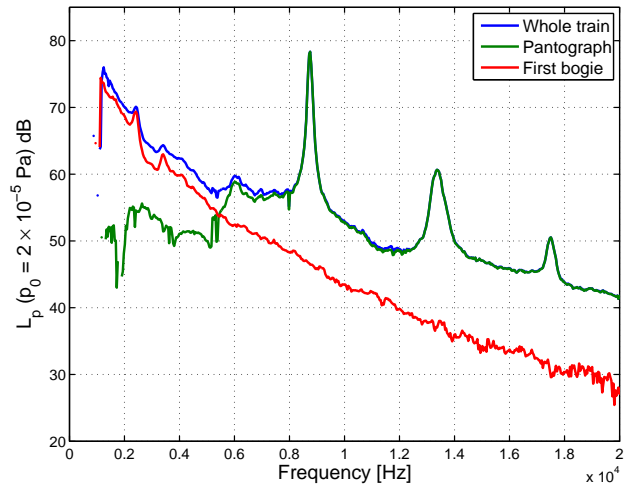


(b) Setup in the test section of the DNW-KKK. Again, the train model is installed on a splitter plate. The microphone array is fixed on the wind tunnel wall. The microphones are flush mounted.

Figure 1. The setups and the two wind tunnels.



(a) Noise maps, sound pressure level colour coded in dB.



(b) Focused spectra for three different scan areas: the whole train, the pantograph and the first bogie.

Figure 2. Measurement at $U_\infty = 60$ m/s, in the AWB.

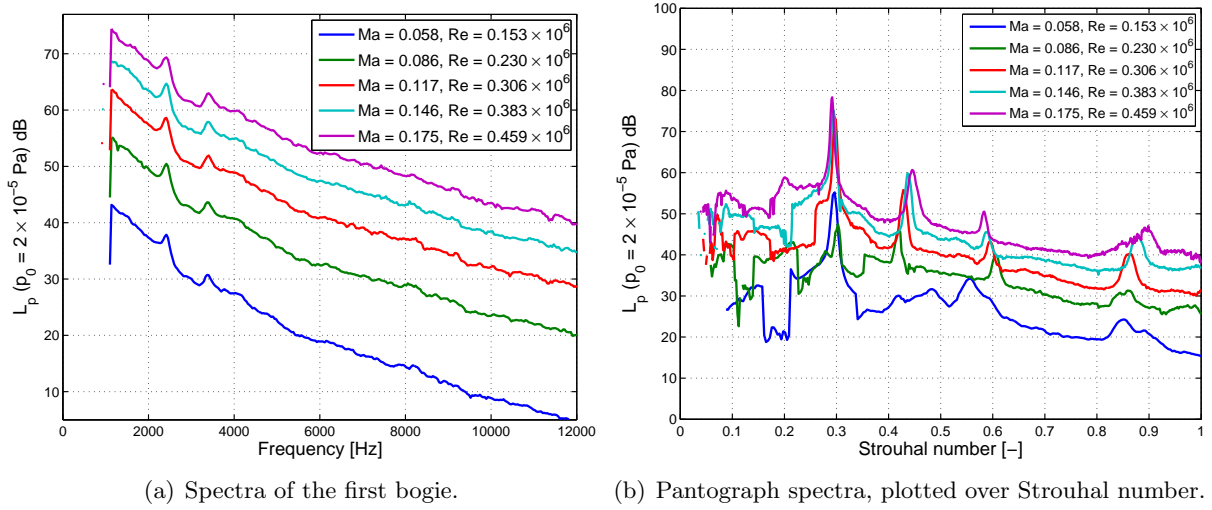


Figure 3. Spectra for different flow velocities, measured in the AWB

B. Measurement in the Cryogenic Wind tunnel (DNW-KKK)

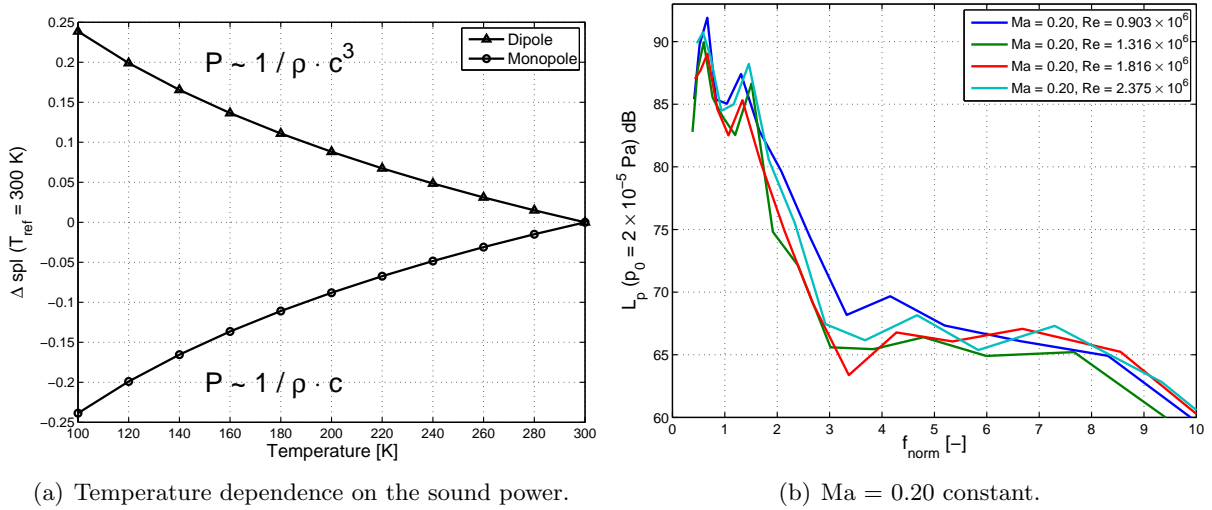


Figure 4. Spectra of the first bogie, measured in the DNW-KKK facility.

The measurements in the aeroacoustic wind tunnel AWB described in the previous section A allow detailed aeroacoustic investigations for Reynolds numbers up to 0.46×10^6 . Compared with a full scale train which operates at $Re > 16 \times 10^6$ this is by a factor of 30 lower and the prediction of the aeroacoustics of a full scale train based on this wind tunnel testings is questionable. Measurements at higher Reynolds numbers are necessary which are presented in this section. As already mentioned in the section III cooling down the fluid is an effective method to increase the Reynolds number. The measurements which are presented in the following have been carried out in

the Cryogenic wind tunnel DNW-KKK in Cologne. This wind tunnel is a Goettingen - type wind tunnel with closed test section with the dimensions 2.4×2.4 m. By injecting liquid nitrogen the fluid can be cooled down to 100 Kelvin. The Mach number can be varied between $0.10 < Ma < 0.30$. Figure 1(b) shows a photo of the setup inside the test section. For the same reason as in the AWB, again the model is mounted on a splitter plate. A microphone array consisting of 144 microphones, arranged in logarithmic spiral arms, is mounted on the side wall of the wind tunnel. for more details see Ahlefeldt et al.²⁰ However, the DNW-KKK has a high background noise level and the closed test section with hard walls causes a reverberant environment. Additionally, it turns out that the used splitter plate produces more self noise compared with the splitter plate of the aeroacoustic wind tunnel. Here, all the mountings underneath the plate are exposed to the flow. All these facts lead to a loss of the signal-to-noise ratio and limit the measurements. Therefore, in the following third octave spectra are shown.

For a detailed investigation of the influence of the Reynolds number on the aeroacoustic source mechanism of the first bogie, measurements at a constant Mach number for different temperatures are plotted. That means, a variation of the Reynolds number is realised by varying the temperature of the fluid. The plots at $Ma = 0.2$ and different Reynolds numbers are shown in figure 4(b). Please note that the data are plotted over the nondimensionalised frequency f_{norm} (equation 7). It turns out that there is no strong influence of the Reynolds number. Within the measuring accuracy the spectra lie on top of each other. The differences in the order of magnitude ± 3 dB can be explained by uncertainties due to the restricted signal-to-noise ratio of the measurements under these difficult conditions. There are no clear tendencies of the relation between sound pressure level and Reynolds number.

V. Outlook

Further investigations with a double model are planed, which is depicted in figure V. This model yields the following benefits:

- Better ground simulation: The flow underneath a full scale train can be characterised by a Couette flow but in the wind tunnel simulations one will obtain a Poisseuille flow. The flow between the plane of symmetry and the bogie cavity should be more comparable to the situation of the full scale world.
- More signal-to-noise ratio: A splitter plate is not needed anymore. The measurements in the cryogenic wind tunnel show that the splitter plate is a strong source of sound, which disturb the measurements

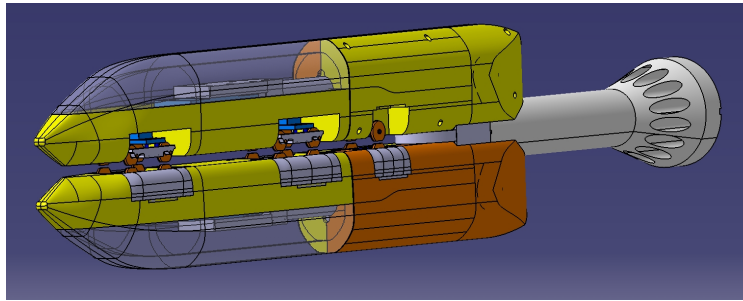


Figure 5. A double model of a train.

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